Power correlations for fuel management studies in LWR's

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Power correlations for fuel management studies in LWR's

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Abstract

In multicycle fuel management studies a certain knowledge of the power distribution between different fuel types is required. It has to be calculated without detailed information on the position of the fuel in the core. Simple correlations to fulfill this requirement are suggested both for PWR's and BWR's.

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INTRODUCTION

In some fuel management studies linear programming is used to find optimal refuelling strategies. The objective of these studies is to minimize the cost of several successive fuel cycles.

To do this a number of different histories for fuel elements are simulated. The costs of these histories are evaluated and are used in the linear programming routine.

A history of a fuel element could be that it is put in the reactor in the first core. When the first refuelling takes place the element is taken out and stored. After two more refuellings it is put back in the reactor but in another region of the core than before, etc. Eventually the fuel element is sold for reprocessing.

The cost of operating a fuel element with a given history will depend on the initial enrichment of the fuel, the value of the created Pu in the discharged fuel, etc.

Of course several elements may have the same operational history and a number of such elements is called a moc. By defining a series of mocs and combining these the fuelling scheme for several cycles is described.

The minimization problem can now be formulated as follows.

It is assumed that the cost of a moc consisting of n fuel elements is n times the cost c of one element. The cost of the fuel cycle is then

$$C = \sum_{i=1}^{N} n_i c_i \qquad (1)$$

where N is the number of mocs defined, n_i is the number of elements in moc i and c_i is the cost of an element in moc i. If n_i is equal to zero, moc number i is not used.

A linear program may then be used to minimize C the variables being n_i.

Some constraints are imposed on the n_i's. The total number K of fuel elements in the core is fixed, that is

$$\sum_{i=1}^{N} n_i = K \qquad (2)$$

The n_i's should also be determined so that the reactivity is large enough to keep the reactor critical. Other constraints may be added but this problem will be treated no further here.

In the course of generating the c_i's the burn up and therefore the power of the fuel elements when they are placed in the core must be known. The burn up must be known, both to be able to decide whether the reactivity constraints are fulfilled and to determine the amounts of Pu and U in the discharged fuel.

Since the costs c_i must be calculated prior to the minimization of C, and since the c_i's depend on the power of the moc, the power has to be found without knowledge of the actual fuel content of the reactor since the n_i's are unknown. Of course, this is in principle not possible. Only an approximate answer may be found by assuming some average fuel content.

DEFINITION OF THE PROBLEM

For the present study the reactor is divided into a number of axial zones (fig. 1)

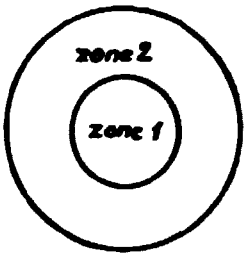


Fig. 1

For each zone the average power density will be specified. Each zone contains N_l mocs and a total of K_l elements, where l is the zone number. It is known which mocs are in the zones. The power distributions within the zones are then to be found. Since the mocs are treated as a whole, and not as a collection of individual fuel elements, the average power density of the

mocs should be found.

It should be noted that because it is specified which mocs are in a zone, the present problem is somewhat different from the one stated in the introduction.

DERIVATION OF A POWER CORRELATION

In some cases the average power density can be assumed proportional to k_∞ of the moc. The power density is then calculated from

$$\bar{P}_i = k_{\infty_i} \bar{P}_1 / \bar{k}_{\infty_1} \tag{3}$$

where $\bar{P}_1$ is the average power density of zone 1 and $\bar{k}_{\infty_1}$ is

$$\bar{k}_{\infty_1} = \sum_{i=1}^{N_1} k_{\infty_i} n_i / K_1 \tag{4}$$

where the previously defined symbols are used. Note that $\bar{P}_i$ is dependent on the number of elements in each moc n_i through $\bar{k}_{\infty_1}$.

To derive (3) consider two neighbouring fuel elements 1 and 2. If we adopt a two group description of the fuel and if the two elements have the same fast flux then the ratio between the power densities will be

$$\frac{\bar{P}_1}{\bar{P}_2} = \frac{\Sigma_{fis\ 1}}{\Sigma_{fis\ 2}} \tag{5}$$

if thermal leakage is neglected Σ_{fis} is defined as

$$\Sigma_{fis} = \Sigma_{f1} + \frac{\Sigma_{21}}{\Sigma_{a2}} \Sigma_{f2} \tag{6}$$

where the usual two group symbols are used. If the fuel elements are not too different in composition then

$$\frac{k_{\infty_1}}{k_{\infty_2}} \simeq \frac{\Sigma_{fis\ 1}}{\Sigma_{fis\ 2}} \tag{7}$$

From this (3) is readily derived.

If the zone 1 is large the fast flux is not constant in

all cases. However, if the fuel is thoroughly scattered so that fuel elements from each moc experience the same average fast flux, (5) is a good approximation since thermal leakage can be neglected in LWR's.

The approximation (7) can as well be avoided by substitute Σ_{fis} for k_∞ in (3) and (4).

In the above derivation it was implied that the fast flux did not wary across a fuel element. If the fuel elements are large, as f.ex. in a PWR, this is not a good approximation. A correction for this will be derived.

An infinite slab of thickness l is surrounded by a homogeneous medium (fig. 2)

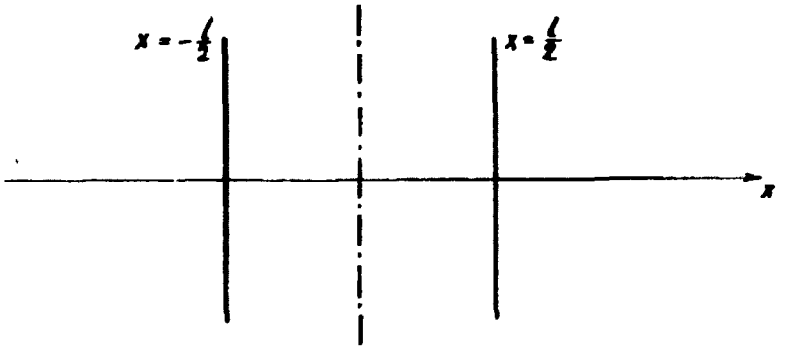


Fig. 2

If the usual symbols are used again the diffusion equation for the fast flux ϕ_1 in the slab is

$$-D_1 \frac{d^2\phi_1}{dx^2} + (\Sigma_{21} + \Sigma_{a1})\,\phi_1 = \frac{k_\infty}{k_{eff}} (\Sigma_{21} + \Sigma_{a1})\phi_1 \qquad (8)$$

where

$$k_\infty = \frac{\Sigma_{f1} + \frac{\Sigma_{21}}{\Sigma_{a2}} \Sigma_{f2}}{\Sigma_{21} + \Sigma_{a1}} \qquad (9)$$

and k_{eff} is the effective multiplication constant for the whole system (slab and homogeneous medium).

The thermal leakage has been neglected again so that

$$\phi_2 = \frac{\Sigma_{21}}{\Sigma_{a2}} \phi_1 \tag{10}$$

where ϕ_2 is the thermal flux. Setting

$$L^2 = \frac{\Sigma_{21} + \Sigma_{a1}}{D_1} \tag{11}$$

(8) becomes

$$\frac{d^2\phi_1}{dx^2} + \left(\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}\right) \phi_1 = 0 \tag{12}$$

For $k_\infty > k_{eff}$ the appropriate solution to (12) is

$$\phi_1 = A \cos \left(x \sqrt{\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}}\right) \tag{13}$$

The ratio of the mean flux of the slab to the flux ϕ_{1e} on the edge, that is, for $x = \frac{1}{2}$, is then

$$\frac{\bar{\phi}_1}{\phi_{1e}} = \frac{\operatorname{tg}\left(\frac{1}{2} \sqrt{\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}}\right)}{\frac{1}{2} \sqrt{\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}}} \tag{14}$$

If $k_\infty < k_{eff}$ then

$$\frac{\bar{\phi}_1}{\phi_{1e}} = \frac{\operatorname{tgh}\left(\frac{1}{2} \sqrt{\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}}\right)}{\frac{1}{2} \sqrt{\frac{\frac{k_\infty}{k_{eff}} - 1}{L^2}}} \tag{15}$$

Defining R_i as

$$R_i = \Sigma_{fis,i} \frac{\bar{\Phi}_{1i}}{\bar{\Phi}_{lei}} \tag{16}$$

where $\bar{\Phi}_{lei}$ is the average edge flux of a fuel element in moc number i. It is proposed to determine the mean power density of moc i in zone 1 as

$$\bar{P}_i = R_i \bar{P}_1 / \bar{R}_1 \tag{17}$$

where

$$\bar{R}_1 = \sum_{i=1}^{N_1} n_i R_i / K_1 \tag{18}$$

$\frac{\bar{\Phi}_{1i}}{\bar{\Phi}_{lei}}$ is calculated from (14) or (15), since these expressions are still valid for a square element if the flux is considered separable. Only $\bar{\Phi}_{le}$ has to be substituted for Φ_{le}.

The above derivation should only be taken as a way of obtaining a physical reasonable expression for the average power density of a moc. Only experience can prove its validity.

TESTING OF THE POWER CORRELATION FOR PWR

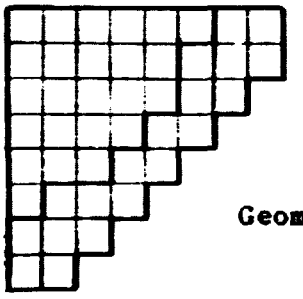
The aim of the correlation (17) was to form basis for power distribution calculations in both BWR's and PWR's. The PWR is simplest to treat since it is not necessary to take into account effects from steam voids in the moderator.

For the purpose of testing the correlation two different core geometries were selected. These cores were loaded with a number of different fuel types in different loading patterns. In the present report results obtained in using three fuel types are shown.

For each loading pattern reference calculations are carried out by means of the two dimensional finite difference equation technique program TWODIM (ref. 1).

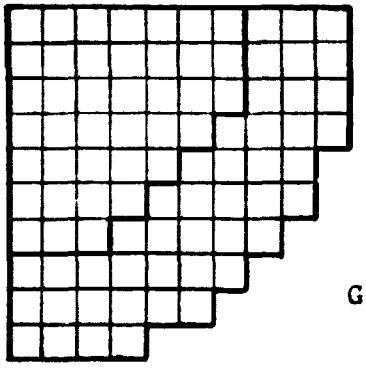
The two geometries are shown below in figures 3 and 4. In both cases the fuel elements are square, having side lengths 20 cm. Only quarter of the core and mirror symmetry was used. The reactors were surrounded by a water reflector, the cross

sections of which were the same for all calculations.



Geometry 1

Fig.3



Geometry 2

Fig. 4

The three fuel types are typical PWR fuels having different enrichments. The complete two group cross sections may be found in appendix 1 Σ_{fis} and k_∞ are given in table 1.

fuel type no.	Σ_{fis}	k_∞
1	0.0360	1.2379
2	0.0257	1.1170
3	0.0215	0.9335

table 1.

For the test calculations the reactors were divided into two zones. The average power density of a moc in a zone determined by (17) is compared to the average power density calculated from

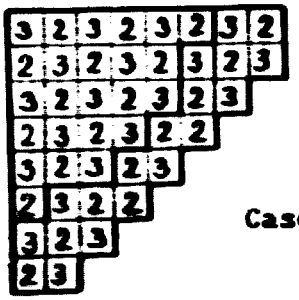
$$\bar{P}_i = \sum_{k=1}^{n_i} P_k \; / \; n_i \qquad (19)$$

where n_i is the number of elements in moc i and P_k is the power density of element k in moc i calculated by TWODIM.

In stead of comparing the average power densities directly, the ratios between average power densities for different mocs calculated from (17) are compared to ratios between power densities calculated from (19).

More than 20 cases were run but only a few characteristic examples will be shown here.

As a first example is taken a checker board pattern of fuel types 2 and 3 in geometry 1 (case 1) as shown in fig. 5.



Case 1

Fig. 5

The results may be found in table 2.

		Fuel type no. 2	3
Relative average power density. TWODIM	outer zone	1.29	1
	inner zone	1.26	1
Relative Σ_{fis}		1.1975	1
ϕ/ϕ_e (equations (14) and (15))	outer zone	1.0452	0.9549
	inner zone	1.0481	0.9568
Relative average power density (17)	outer zone	1.31	1
	inner zone	1.31	1
Relative k_∞		1.1966	1

table 2
case 1

In the second example (case 2) again a checker board pattern was used. Only fuel type 3 was replaced by 1 and 2 by 3. Results in table 3.

		Fuel type no. 1	3
Relative average power density TWODIM	outer zone	2.35	1
	inner zone	2.06	1
Relative Σ_{fis}		1.6690	1
Relative average power density (17)	outer zone	2.00	1
	inner zone	1.99	1
Relative k_∞		1.3261	1

table 3
case 2

From table 2 and 3 it appears that the results obtained from (17) are good in the case of a checker board loading pattern and Σ_{fis} not too different for the two fuel types.

It is also noted that

$$\frac{\Sigma^2_{fis}}{\Sigma^3_{fis}} \simeq \frac{k^2_\infty}{k^3_\infty} \qquad (20)$$

for case 1.

In case 2 the results are acceptable, the larger deviation in power density ratio calculated from (17) from the correct value being $\simeq$ 15%.

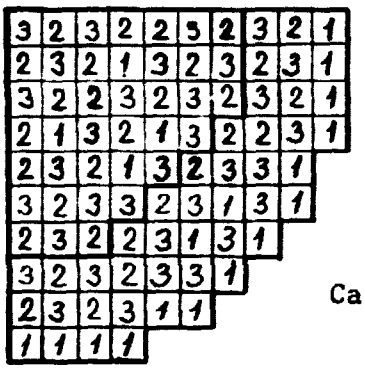
In this case, in which the ratio between the fission cross sections is larger than for case 1, it is seen that a considerable improvement has been achieved in using fission cross sections in stead of k_∞ for calculating the power density ratio.

It is to be expected that the checker board loading scheme should be one of the simplest cases to cope with by means of a correlation like (17). The average fast flux experienced by both fuel types will be the same. F.ex. the flux gradient at the edge of the core will have the same effect on both types.

If the core contains more than two fuel types the situa-

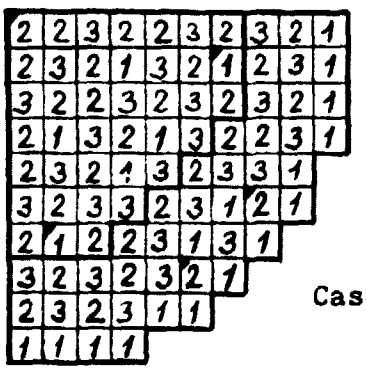
tion becomes more complicated. This is illustrated in the following two examples where the core is loaded with three fuel types.

The fuel distributions for the two examples are shown in figures 6 and 7 (case 3 and case 4)



Case 3

Fig. 6



Case 4

Fig. 7

Only very few changes are made between case 3 and case 4. In the center a type 2 element has been substituted for a type 3 in order to increase the flux in the center of the core. To get a better distribution of the fuel, two type 1 elements have been put into the center zone and two type 2 elements have been put into the outer zone in stead of type 3 elements.

Because of these changes the overall form factor calculated by TWODIM is decreased from 3.47 to 2.74.

The results are found in table 4 and 5.

		Fuel type no. 1	2	3
Relative average power density TWODIM	outer zone	1.41	1.36	1
	inner zone	2.91	1.34	1
Relative average power density (17)	outer zone	1.98	1.30	1
	inner zone	2.03	1.31	1
Relative Σ_{fis}		1.6690	1.1975	1

Table 4, Case 3

		Fuel type no. 1	2	3
Relative average power density TWODIM	outer zone	1.36	1.25	1
	inner zone	2.26	1.23	1
Relative average power density (17)	outer zone	1.97	1.30	1
	inner zone	1.98	1.29	1
Relative Σ_{fis}		1.6690	1.1975	1

Table 5, Case 4

Some conclusions may be drawn from these results.

If, at first, the results for the inner zone are considered it is seen that if only a few elements of a given type are put in a zone, and if in addition these are very different

from the rest of the fuel in this zone, results obtained by a correlation like (17) can be rather poor. It appears that if (17) is to give good results either the fast flux and thus the power should be flat within a zone, or if a flux gradient exists across a zone, the fuel must be loaded in such a way that each fuel type experiences the same average fast flux (as was the case for a checker board pattern).

This last fact is clearly illustrated by the results from the outer region. In order to get a low form factor the fuel having the largest Σ_{fis} (type 1) was put along the edge of the core. This, of course, means that the average power density of fuel type 1 becomes low in this zone.

The results from case 2 and the results from case 3 and 4 for fuel types 2 and 3 confirm that (17) yields good results if the fuel is thoroughly mixed,even in case of the strong flux gradient across the edge zone of a core.

From cases 3 and 4 it is also apparent that arranging a given combination of fuel elements within a zone in different ways may give quite different average power densities for each fuel type. Any correlation like (17), which does not take the position of the fuel into account, will of course not detect such differences. Thus even when a good power correlation has been found,one should always expect rather large errors in some cases.

Lastly it should be mentioned that it was tried to divide the core into zones different from the ones shown and also to use fuel element with different side lengths without the above conclusions being altered.

BWR POWER CORRELATION

As previously stated it is expected to be more difficult to obtain a power correlation for a BWR. In a BWR there is a strong coupling between the power and steam voids in the moderator.

The usual method for calculating the power distribution consists in an iterative process where a power distribution is calculated based on results from a hydraulics calculation. From the power distribution a new hydraulics calculation is performed etc.

The void dependence of the power also necessitates three dimensional power distribution calculations. Since the PWR power correlation was partly based on the fact that the power distribution in a PWR may be found from a two dimensional calculation it is not to be expected that this correlation can be used for BWR's, even if allowances are made for the void dependence.

However, it was tried to use the PWR correlation in the following manner. Assuming zero void in the reactor the average power density for each fuel type was found from (17). From this the average void content for each type of fuel elements may be found by making some reasonable assumptions about the vertical power shape and the coolant flow in each fuel element type. Based on the average void content new Σ_{fis} may be calculated and thus (17) may be used again. This procedure continues as in a normal BWR power distribution calculations.

This method was tried in some cases. The vertical power shape was assumed sinsoidal and all fuel elements had the same coolant flow.

It turned out to be not very successfull. If, on the other hand, the moc power densities were determined simply by

$$\bar{p}_i = \Sigma_{fis,i}\, \bar{p}_1 / \bar{\Sigma}_{fis,1} \qquad (21)$$

where $\bar{p}_i$ is the average power density of moc i, $\bar{p}_1$ is the average power density of zone 1 and all Σ_{fis},s are calculated at 0% void, accaptable results were obtained as it will be shown below.

AVERAGE VOID FRACTION

When the average power density for a moc is calculated the void content of the fuel elements was not used. However, since burn up calculations are carried out in fuel management studies and since the burn up and build up of nuclei in the fuel depend on the void fraction via the neution spectrum, the average void fraction of a fuel type must be known.

To calculate this the following simple model may be used:

The void fraction at some distance from the inlet of a fuel element is

$$\alpha = \frac{1}{1 + \frac{1-x}{x} S \frac{\rho g}{\rho f}} \tag{22}$$

where x is the steam quality $x = \frac{W_g}{W_g+W_f}$. W_g and W_f are the mass flow rates of steam and water respectively.

S is the slip. S is assumed constant ($V_g = SV_f$ where V_g and V_f are steam and water velocity).

ρ_g, ρ_f are the densities of steam and water.

Setting $S = 1.3$ and taking the values for ρ_g and ρ_f at saturation conditions at 70 bar (22) becomes:

$$\alpha = \frac{1}{1 + 0.064\frac{1-x}{x}} \tag{23}$$

The steam quality at distance z from the inlet may approcimately be determined from

$$x = \frac{Q}{h_{f_g} W_t} \int_0^z f(y) d_y \tag{24}$$

where the inlet subcooling is assumed to be zero and where

h_{f_g} is the enthalpy of evaporation.

W_t is W_g+W_f.

Q is the total power of the fuel element.

$f(y)$ is the normalized vertical power shape.

If f(y) is sinusoidal

$$f(y) = \frac{\pi}{2l} \sin \frac{\pi y}{l} \tag{25}$$

where l is the length of the fuel element, the average void fraction becomes

$$\bar{\alpha} = \frac{1}{l} \int_0^l \frac{dz}{1 + 0.064 \left(2 \frac{h_{f_g} W_t}{Q} \frac{1}{1-\cos\frac{\pi z}{l}} - 1\right)} \tag{26}$$

which for not too small $\frac{Q}{h_{f_g} W_t}$ (> 0.03)

becomes

$$\bar{\alpha} \quad 1 - \frac{0.064 \frac{h_{f_g} W_t}{Q}}{1 + 0{,}064 \frac{h_{f_g} W_t}{Q}} \tag{27}$$

h_{f_g} is taken at saturation conditions at 70 bar, that is

$$h_{f_g} = 1.505 \cdot 10^6 \text{ Joule/kg}$$

For W_t is used the average flow rate pr. fuel element. Normally W_t is dependent on Q and in principle it would be possible to build this dependence into the model.

However, for this purpose where shcrt computing time is essential the average flow rate is believed to be satisfactory.

TEST EXAMPLES FOR BWR's

In this case only one geometry was used. It is shown below in fig.8. Main data may be found in appendix 2.

The reference power distribution was found by means of the coupled three dimensional nodal theory-hydraulics program NOTAM. The fuel elements were 12.5 cm square but because of restrictions in the hydraulics of the program in the present version of NOTAM, four adjacent elements had to be of the same type so that the effective fuel elements were 25 cm square.

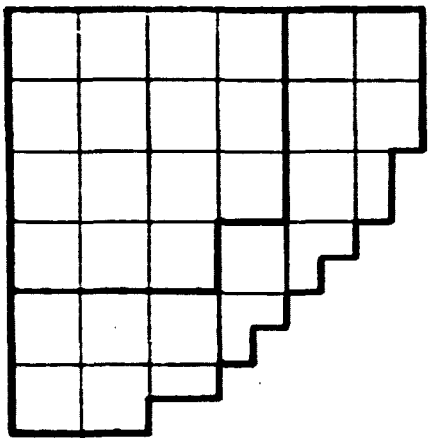


Fig.8.

Similar to the PWR case the average power density of each fuel type is calculated. The ratio between these average powers are then compared to those obtained from (21).

Three types of fuel elements were used. The cross sections may be found in appendix 2. k_∞ and Σ_{fis} for all types at zero void are given in table 6.

fuel type nro.	k_∞	Σ_{fis}
1	1.0130	0.0290
2	1.1373	0.0326
3	1.2059	0.0345

table 6.

Again the reactor was divided into two zones as shown in fig.8. And again as a first example is taken a checker board loading pattern of fuel types 1 and 3. (fig.9). Results are presented in table 7.

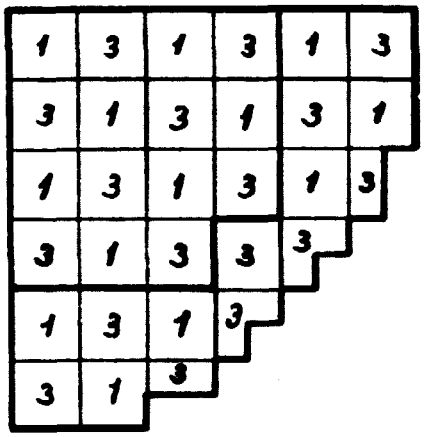


Fig.9 case 5

		Fuel type no. 1	3
Relative average power density NOTAM	outer zone	1	1.17
	inner zone	1	1.19
Relative Σ_{fis}		1	1.19
Relative k_{∞}		1	1.19

table 7 case 5

As in the PWR-case the result is good.

In the following case the fuel composition of the internal zone is modified by substituting two type 3 elements by type 2 elements as shown in figure 10. Results in table 8.

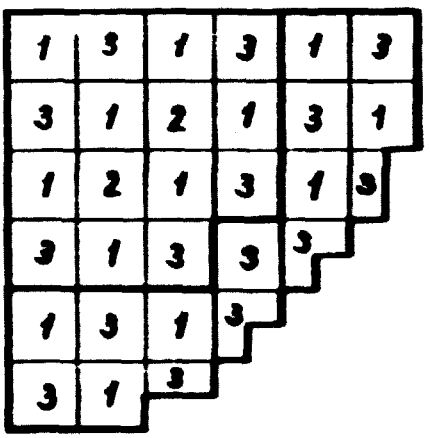


fig.10 case 6.

		Fuel type no. 1	2	3
Relative average power density NOTAM	outer zone	1	-	1.27
	inner zone	1	1.08	1.19
Relative Σ_{fis}		1	1.12	1.19
Relative k_∞		1	1.12	1.19

Table 8 case 6

In case 7 the two type 2 elements are moved to the edge of the inner zone, and as expected the average power density of type 2 becomes lower and at the same time that of type 3 becomes higher. Also notice the change of the power density in the outer zone. (Table 9).

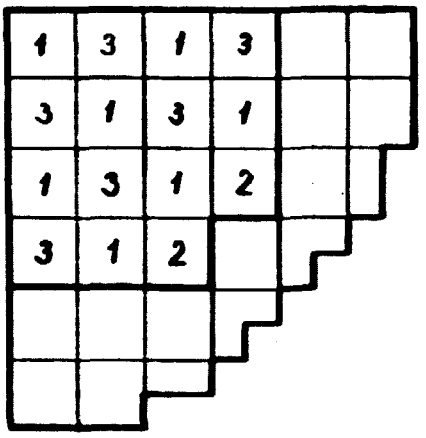


Fig.11 case 7

		Fuel type no. 1	2	3
Relative average power	outer zone	1	-	1.25
Density NOTAM	inner zone	1	0.82	1.28
Relative Σ_{fis}		1	1.12	1.19

Table 9 case 7.

Finally in cases 8 and 9 two and four additional type 2 element are put into the internal zone. (Figures 12 and 13 tables 10 and 11).

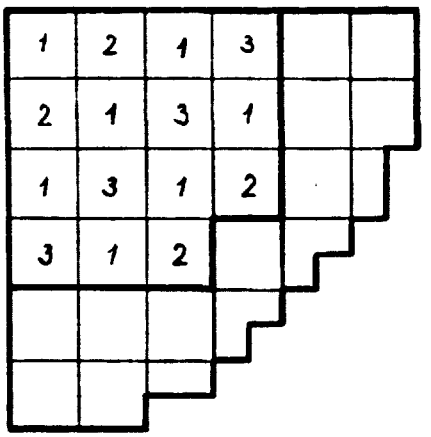


fig.12 case 8

		Fuel type no. 1	2	3
Relative average power	outer zone	1	-	1.34
Density NOTAM	inner zone	1	1.07	1.28
Relative Σfis		1	1.12	1.19

Table 10 case 8.

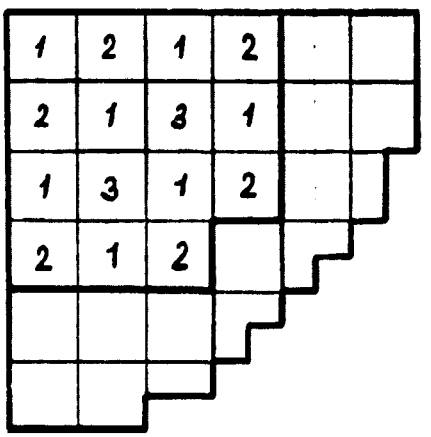


fig.13 case 9.

		Fuel type no. 1	2	3
Relative average power	outer zone	1	-	1.12
Density NOTAM	inner zone	1	1.04	1.30
relative Σ_{fis}		1	1.12	1.19

Table 11 case 9.

From these results mainly the same conclusions as for the PWR-case may be drawn.

If the fuel is thouroughiy mixed (21) is expected to give good results. However, if the mixing is not sufficient the average power density of a certain fuel type may be rather sensitive to the position of the fuel. Notice in this connection the variation in average power density in the outer region when the composition of the inner region is changed.

REFERENCES

1) K.E. Lindstrøm Jensen, Development and Verification of Nuclear Calculation Methods for Light-Water Reactors. Risø Report No. 235 (1970) 161 pp.

APPENDIX 1

CROSS SECTIONS FOR THE PWR CASE

All cross sections are given in the following format

D_1	D_2
$\Sigma_{a1} + \Sigma_{21}$	Σ_{12}
Σ_{21}	Σ_{a2}
$\nu\Sigma_{f1}$	$\nu\Sigma_{f2}$
Σ_{f1}	Σ_{f2}

Fuel type 1

1.371	3.940E-01
2.906E-02	0
1.898E-02	8.285E-02
6.963E-03	1.267E-01
2.624E-03	5.211E-02

Fuel type 2

1.511	4.631·E-01
2.304E-02	0
1.571E-02	4.243·E-02
4.098E-03	5.843E-02
1.556·E-03	2.403E-02

Fuel Type 3

1.511	4.657E-01
2.307E-02	0
1.564E-02	4.870E-02
4.092E-03	5.433E-02
1.553E-03	2.235E-02

Reflector

1.347	2.835E-01
3.662E-02	0
3.534E-02	2.540E-02
0	0
0	0

APPENDIX 2

DATA FOR THE BWR-CASE

Thermal power	420 MW
Coolant flow, total	1840 kg/sec.
Average void	28.5%

Cross sections.
In this case the format is:

D_1	D_2
Σ_{a1}	
Σ_{21}	Σ_{a2}
$\nu\Sigma_{f1}$	$\nu\Sigma_{f2}$

Fuel type 1

void fraction		
0	1.44	0.584
	0.648E-02	
	0.221E-01	0.387E-01
	0.331E-02	0.449E-01
0.3	1.58	0.650
	0.629E-02	
	0.183E-01	0.370E-01
	0.318E-02	0.437E-01

0.6	1.80	0.788
	0.617E-02	
	0.144E-01	0.381E-01
	0.327E-02	0.490E-01

Fuel Type 2
void fraction

0	1.44	0.662
	0.677E-02	
	0.219E-01	0.451E-01
	0.386E-02	0.592E-01
0.3	1.58	0.729
	0.658E-02	
	0.181E-01	0.431E-01
	0.372E-02	0.574E-01
0.6	1.80	0.828
	0.631E-02	
	0.143E-01	0.407E-01
	0.353E-2	0.549E-01

Fuel type 3
void fraction

0	1.44	0.729
	0.705E-02	
	0.216E-01	0.496E-01
	0.437E-02	0.693E-01
0.3	1.58	0.797
	0.684E-02	
	0.179E-01	0.473E-01
	0.422E-02	0.669E-01

0.6	1.80	0.895
	0.657E-02	
	0.141E-01	0.446E-01
	0.403E-02	0.638E-01

For all fuel type ν = 2.43.